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MEMORANDUM

TO: Janice Sylvestre
FROM: Mark Woodbury
DATE: 30 April, 2004
SUBJECT: General Streamflow Regulation Modeling Strategies

Background

As part of its plan to provide an Advanced Hydrologic Prediction Service (AHPS), the National Weather Service (NWS) is using the NWS River Forecast System (NWSRFS) to prepare long-range probabilistic forecasts of streamflow. The presence of extensive systems of streamflow regulation to capture and re-regulate or divert runoff in many parts of the country require additional data, effort, and new procedures to characterize and accurately predict the effect of this regulation for developing forecasts.

As an initial step in developing national implementation strategies, a document titled "*Streamflow Regulation Issues and Solutions Identification"* (*Issues Identification*) was distributed to each RFC. The document included a request for feedback and responses were received from every RFC. RTi prepared a memo dated 22 March, 2004 summarizing feedback from the RFCs. This memo presents initial thoughts on modeling strategies to guide future development and implementation activities and efforts.

In considering recommendations for national strategies, we have identified important functions that can be arranged in two groups based on the locus of activity for` these functions. One set of functions seems best dealt with at regional and national levels with input and direction from regional and national Hydrologic Services Divisions (HSD), as well as from the Office of Hydrologic Development (OHD). These are addressed below under national management team (NMT) functions. Another set of functions pertains more directly to individual RFCs and are addressed under RFC functions.

NMT Functions

Important functions that the NMT may have in facilitating streamflow regulation accounting could include strategic planning, development and support.

Strategic Planning

One of the important issues identified by RFCs is defining standards for accuracy consistent with resources available for implementation and operations. This is an area in which the NMT could provide guidance and take the lead in proposing appropriate levels of modeling to account for regulation effects. This will require consideration of the required accuracy of the regulation models and resulting forecast products, the variety and complexity of the regulation issues, the effort and cost associated with their modeling, and the overall resources available for dealing with streamflow regulation on a national scale.

Development

As seen in the RFC responses to the *Issues Identification* document, the streamflow regulation issues vary somewhat from area to area. Although many of the same tools will be used by all the RFCs, individual RFC development priorities for enhancements and new tools may be very different. The NMT must play an important role in evaluating technologies, establishing priorities, allocating resources, and coordinating the development, enhancement, and maintenance of tools for modeling regulation.

Support

An important element from the evaluation of the RFC responses was the need for ongoing efforts to familiarize RFC staff with available tools and for RFCs to share ideas and experience with one another. Both of these objectives are facilitated through organization of training workshops for RFC staff. These should include training on existing tools and procedures together with ample time for RFCs to present case studies of modeling approaches and implementations and to pose modeling challenges and obtain feedback from participants. The frequency of these workshops should reflect the priority of regulation issues in comparison to that of other issues that effect the quality of forecasts. Based on case studies prepared by RFCs, a library of solutions could be maintained as a resource for other RFCs to draw upon.

RFC Functions

RFC functions are focused on implementing solutions within the RFC area. Perhaps a first step that should be taken would be to list and prioritize unresolved regulation issues for the RFC area. The prioritization should include a consideration both for the degree of regulation effect as well as the difficulty of accounting for it. The top priority may not go to the most difficult problem, but rather to a simpler issue that can be resolved at a reduced cost or with a greater benefit to the accuracy of the resulting forecast. It may be best to postpone the resolution of some issues if there is a reasonable expectation that a new or enhanced tool appropriate to that issue will be available in the near term. Other considerations in prioritizing implementation efforts include locations with the greatest need for AHPS as well as upstream areas that must be completed prior to downstream implementation.

RFCs should continue to be actively involved in defining requirements for new tools and enhancement to existing tools that could be proposed to NMT, as well as participating in the discussion of accuracy standards and development of expectations. Constructive approaches that might be considered include developing proposals for investigations, documenting implementation efforts and challenges, and developing and reporting on pilot implementations of new model approaches. Active participation in training workshops can also help both to increase the capabilities of RFC staff as well as to share ideas on modeling approaches.

Based on its implementation priorities, staff capabilities and other resources, each RFC then needs to work through its unresolved regulation issues, starting with highest priority ones. The following section outlines a general implementation approach that could be tailored to a given streamflow regulation challenge.

Implementation Approach

This section outlines an approach to implementation of a given regulation issue. It is directed toward a basin-wide regulation challenge but could be simplified to be applied to a single regulation issue by abbreviating or eliminating unnecessary steps. The major activities include a basin inventory, data analysis and synthesis, design and testing of alternatives, and implementation in NWSRFS.

Basin Inventory

Objective

Collect as much information as possible in order to adequately understand the regulation in the river basin. The primary questions that need to be answered at this stage are 1) WHAT types of regulations are affecting the river, 2) WHERE are these regulations occurring, 3) WHO is responsible for the regulations, and 4) WHY do they operate as they do. This information provides the basis for making qualitative assessments of the relative streamflow impacts caused by the various regulation issues.

Steps

Basin Overview: Briefly describe the basin characteristics, major water uses, and other important facts.

Regulation Identification: Identify both regulation types and regulating entities within the forecast area.

- Identify Types of Regulation: Regulation can occur in many shapes and forms. Most often regulation is associated with a physical structure such as a dam or diversion canal, but can also occur as a result of administrative rules and policy.

- Identify Regulators: Regulators can be both the entity owning/operating a regulation structure as well as an agency responsible for enforcing/administering river flows.

- Establish Contacts with Major Regulating Entities: After identifying regulators, contacts within the regulating entity must be established in order to gain access to data and information.

Information Collection: Several different types of information are required to fully describe streamflow regulation.

- Data: Time series observations including streamflow, diversions, reservoir levels and releases, and other hydrologic features are usually collected and maintained by a government agency.

- Basin Administration: Administrative records provide an overview of the past water years and typically highlight any type of exceptional operational action.

- Operational Information: Published operational reports, such as annual operating reports for Bureau Projects, regulation manuals for USACE projects provide the basis for developing operational rule curves. Many private regulating entities do not publish reports making data acquisition more difficult.

- Existing Studies and Reports: Hydrologic/Engineering studies are an important resource and can provide a significant amount of insight into the river system.

- GIS / Maps: USGS quad maps and GIS data provide the means to identify spatial distribution and location of regulating structures.

High Level Basin / Segment Characterization: Before in-depth analysis begins, the basin should be evaluated and characterized to identify strategic issues

- Characterize Segments: Characterize in terms of general hydrology, operations, and administration.

- Identify Key Regulation Points and Practices: Major regulations/regulators that have the capacity to affect multiple segments must be identified.

Data Analysis and Synthesis

Objective

Isolate and analyze regulations in each individual segment and then synthesize this information at a system level. The intent is to define the cause and effect relationships between the streamflow and the regulation. Success in this task will be largely determined by the quality of information collected in the earlier stage. The next step is to consider those regulations that transcend the boundary of a single segment and to measure their range of influence, both upstream and downstream. Ultimately, we would like to understand how all of the different regulators/regulations interact and affect one another and how they manage to operate together in a single, comprehensive system.

Ultimately, there are 3 effects of regulation on streamflow: increase flows (imported water), decrease flows (divert and consumptively use), or alter the timing of flows (dams). Many forms of regulation will be responsible for more than one effect.

Steps

Formulate Analysis Tools: Data and information management pose a particular challenge in this stage. The investigator must merge information and data from multiple sources and formats.

Control Volume Diagram: Diagrammatic and quantitative segment analysis provide the basis for understanding streamflow regulation.

- Diagram inflows and outflows: Develop a diagram showing inputs and outputs from each segment.

- Segment Mass Balance: This is a basic mass balance approach to identifying the timing and magnitude of the inflows / outflows occurring within each segment.

- Naturalized Flows: Naturalized flows can be calculated by adding/subtracting regulating effects at the downstream gage. These results may be helpful for calibration purposes.

Aggregate Regulations: Regulations that have similar operations and effects upon streamflow should be considered as candidates for aggregation.

Classify Regulations by Level of Impact: Regulation can be classified by magnitude, frequency of occurrence, seasonality, and other relevant factors.

Identify System Dynamics: Establish a comprehensive overview of regulation effects. Classify local (within segment) and system (spanning several segments) regulation.

Design and Test Alternatives

Objective

Associate streamflow regulation issues with viable strategies using NWSRFS operations to represent regulation in the basin. Regulating operations, and the rules that govern them, must be conceptualized in such a manner as to be translated into the NWSRFS modeling environment. This process must be performed on a segment-by-segment basis for localized regulations, as well as on a more global level for overarching regulations.

Steps

Identify alternatives: Consider a variety of approaches to represent various streamflow regulation issues. Identify strengths and weaknesses. Evaluate the acceptability of resulting complexity.

Outline modeling plan: Select from alternatives and outline the models and modeling approach to be used for each segment. The term "segment" is used loosely here to refer to simulation/forecast points, since new segments may be introduced to handle local flow calculation and other time series manipulation operations.

Note: this may be a place where one would recommend alternative forecast locations because: a) the streamflow at the existing forecast point is so heavily regulated that it is impossible to accurately simulate, or b) a location just upstream or downstream would provide more useful data to decision makers/ regulators.

Another item to be considered at this stage is whether or not the existing rainfall – runoff model calibrations have already built in some of the effects of regulation. If natural flows were developed previously, they could be used to recalibrate the segment so that it is appropriate in combination with the regulation simulation.

Test modeling approaches: It is likely that the modeling approaches will include one or more combinations of operations that have not been tried before in the exact manner chosen. The more innovative modeling approaches should be tested in a pilot implementation for conceptual flaws and overall ability to represent the regulation issue.

NWSRFS Implementation

Objective

Develop and implement the design in the operational forecast system.

Steps

- *Calibrate NWSRFS operations:* Assemble calibration decks with appropriate operations and adjust model parameters and selected modeling components through successive simulations to capture regulation effects.

- *Evaluate the success of the models:* Consider the degree of improvement in capturing regulation effects compared to the previous modeling approach. Test the implementation in an ensemble forecast mode to verify proper functioning and to evaluate results, including the use of "hindcasting."

- *Redefine system*: Redefine the segments and the structure of the forecast system configuration as needed.

Specific strategies

The following material presents specific ideas for the use of existing NWSRFS operations to represent streamflow regulation. Ideas for enhancements to existing tools, development of new tools, modifications to forecast system structure, and the use of external models are presented in an appendix.

Use of Existing Tools

The National Weather Service River Forecast System (NWSRFS) already includes many tools in the form of NWSRFS operations which are actively being used to model streamflow regulation issues. Many creative examples of combining existing operations were presented in the summary of responses from the RFCs to the *Issues Identification* document. The existing operations that will be of most value in streamflow regulation modeling strategies are listed below.

CONS_USE

The Consumptive Use Operation was designed to model surface water diversions and return flows resulting from irrigation. Based on estimates of potential evapotranspiration, the irrigated area, monthly crop coefficients, and an irrigation efficiency factor, the consumptive use model estimates the crop demand for water and the diversion necessary to satisfy it. In addition, a return flow accumulation coefficient and routing coefficient are used to simulate the irrigation return flows. The operation must be used in conjunction with the Sacramento Soil Moisture Accounting model in order to simulate the water balance over the irrigated parcel, by accounting for precipitation and any runoff. The model assumes that return flows return to the stream at the diversion point and are available for diversion. The model limits the computed diversion to the water available in the stream less any minimum required streamflow.

Because the operation has been designed to simulate irrigation diversions based on climate, it is able to estimate diversions and return flows in a long-term forecast. The operation was not designed to simulate irrigation from ground water pumping and its impact on surface water discharge. In addition, the operation does not account for any constraints on diversions due to water rights or conservation restrictions. In areas with prior appropriation water rights, actual diversions may be based more on water rights than on daily climate and crop demand.

CHANLOSS

The CHANLOSS operation was developed to simulate losses or gains from a channel reach. The losses/gains can be specified as average monthly values or as monthly percentages of the channel flow. In cases where diversions are consistent from year to year and where there is little day to day variability, the diversions can be effectively modeled with the CHANLOSS operation. The CHANLOSS operation may work well for many municipal and industrial use diversions, as well as irrigation diversions that are governed more by reliable water rights. This operation may not work well for junior water rights that are often constrained by the water supply.

RES-J

The RES-J operation was developed as a network model, which could simulate a network of reservoirs, reaches, and nodes. Many reservoirs are operated based on conditions in other parts of the river system, e.g., the states of other reservoirs or flooding conditions at locations which serve as control points. RES-J includes a number of methods which simulate reservoir releases as a function of pool elevation and date. RES-J uses rules specified by the user to control which methods are activated based on conditions in the network. Rules can be written using Boolean expressions based on inflows, outflows, pool elevations, flow at a node, or dates. The design of RES-J considered the need to simulate reservoir releases for both short-term deterministic forecasts as well as long-term ensemble forecasts.

For simple applications it may be possible to parameterize the RES-J model based on known reservoir operations, however, in most cases it is necessary to calibrate the model using recent historical data.

RES-SNGL

The RES-SNGL operation was developed to model a single independently operated reservoir. It includes a set of schemes to simulate the different operating modes of a reservoir. It also includes a Reservoir Command Language (RCL) that allows the user to control switching from one mode to another based on the states of the reservoir, e.g., pool elevation, inflow, outflow, and date. The functionality of the RCL is very similar to the rules in RES-J. Many of the schemes and utilities can be combined to provide valid short-term deterministic forecasts as well as long-term ensemble forecasts.

SSARRESV

The SSARRESV operation is based on the Streamflow Synthesis and Reservoir Regulation System developed by the U.S. Army Corps of Engineers and the NWRFC. The operation routes water through a reservoir under 'free flow' or 'controlled flow' modes of operation. Flows may be routed as a function of multivariable relationships involving backwater effects from a downstream reservoir. During the forecast period, the operating mode must be expressed through run-time modifications. The need to specify the future simulation mode rather than determine it based on the reservoir state limits the length of the future period over which valid forecast information can be produced.

LOOKUP

The LOOKUP operation provides the ability to compute an output time series as a function of an input time series. The function is described as a table which relates the output time series value to the input time series value. This is an extremely flexible operation that can be used in clever ways to do many different things. This operation can be used to compute a diversion which is any known function of a discharge time series as long as the function does not vary in time.

LOOKUP3

The LOOKUP3 operation provides the ability to compute an output time series as a function of 2 input time series. The most common use of this operation is in backwater situations where the river stage is a function of discharge in a tributary as well as in the main stem. The LOOKUP3 operation could be used to compute a diversion as a function of a crop demand time series and a water supply forecast (i.e., if the water supply forecast can be supplied as a time series.).

FLDWAV

The FLDWAV operation is a generalized routing model that provides multiple routing techniques including a four-point implicit finite difference numerical solution of the Saint Venant equations. It includes internal boundary conditions representing downstream dams, bridges, weirs, waterfalls and other flow controls.

SAC-SMA

The SAC-SMA operation provides a conceptual soil moisture accounting model that enables the user to compute a water balance over an area based on inputs of precipitation and potential evapotranspiration. Modelers have used large values of UZTWM to account for small pond storage, and negative values of SIDE to account for unusual winter groundwater return flow.

DELTA-TS

The DELTA-TS operation computes the rate of change of values per time interval for a time series. The most common use of the operation is to compute the change in reservoir storage from a reservoir storage time series.

TATUM

The TATUM routing model can be used to divide the flow into layers that have different routing parameters that effectively divide and redirect the flow. For example, the TATUM operation could be used to model a diversion where all flows from 0 – 200 cfs remain in the channel, 50% of the flow from 200 – 400 cfs is diverted to another basin, and the remaining flow above 400 cfs remains in the channel.

ADD-SUB, MULT/DIV, SET-TS, WEIGH-TS

These operations allow the user to manipulate time series in different ways that may be useful in constructing operations tables that attempt to model streamflow regulation.

Appendix – Additional Development

As higher priority is placed on accounting for streamflow regulation in forecast operations, development will be required to extend the capabilities of NWSRFS. Ideas for new development and their associated priorities will surface regularly as NWS addresses new regulation issues and acquires experience in implementation. Below is an initial list suggested for development based on RTi's experiences to date. Any development associated with these items would necessarily follow the OHD development process for software if it is to be included in the OHD baseline. Requirements that are identified in the future should be documented and sent forward consistent with the existing requirements process. Following is an initial list of ideas for development that might be considered to facilitate streamflow regulation modeling. Priorities are associated with each proposed enhancement. These priorities reflect RTi's experience and perspectives, and are influenced by our current work for NWS in the South Platte basin.

Potential Enhancements to Existing Tools

Enhancements to existing operations would provide additional flexibility in modeling streamflow regulation.

CONS_USE

A number of RFCs have used the CONS_USE operation to simulate irrigation diversions. Several enhancements could be made to provide more flexibility in its application.

1. Diversions from a point on the river are often made to meet agricultural consumptive use demands. The actual diversion may be a function of a number of variables including the demand, current streamflow at the diversion or at another point in the system, available storage that could be released to meet the demand, and other higher priority demands at downstream locations, among others. Diversions are often transferred downstream or to adjacent basins before they are applied. Irrigation return flows then appear near the point of irrigation rather than at point of diversion. The current consumptive use model is limited in that it assumes that only the existing streamflow is available to meet the demand, and that return flows occur at the point of diversion and are available to be diverted again.

   Flexibility to simulate a variety of circumstances that differ from the constraints of the current CONS_USE operation could be obtained by allowing the demand and return flow components of the model to be isolated. The demand component would compute consumptive use demand without regard to available supply. The diversion could be computed within the model or in a separate operation, and the return flow could be made a function of the internally computed demand and diversion or as a function of externally supplied demand and diversion time series. This could be done in such a way as to retain the current capability of the model while adding significant additional flexibility. *Priority: High*

2. Consumptive use demand may be met in whole or in part by precipitation over an irrigated area. This often results in a temporary reduction in diversions. This effect is not modeled currently by the CONS-USE operation and represents a limitation in its capability. An MAP input time series could be introduced to the operation together with an accounting for the demand satisfied by precipitation. *Priority: Moderate*

RES-J

RES-J has proven to be a very useful model for simulating reservoirs, even when the operating rules are not explicitly known. The overall computational efficiency of RES-J should be investigated in order to improve its performance. In addition several enhancements would improve its functionality.

1. Many reservoirs are operated to limit downstream flooding at a point that also receives flow from an unregulated tributary. The MAXSTAGE method was included in RES-J to provide the capability to model this type of operation. The current method, however, is unstable and computationally inefficient. Improvements could be made to the MAXSTAGE method in RES-J to ensure its stability and make it computationally more efficient. The main functionality could be maintained with a simpler approach. *Priority: Moderate*

2. Many reservoirs are operated or can be simulated by specifying releases in part as a function of other variables in the system, such as the pool elevation at another reservoir, a downstream flow, the elevation at the reservoir making the release, or a combination of these variables. This type of operation could be represented with a new method in RES-J with the functionality found in LOOKUP3. *Priority: High*

   The rules capability also could be enhanced to allow testing on additional variables, e.g., time series values and linear combinations of states. *Priority: Low*

3. RES-J lacks the capability to access intermediate candidate releases as they are successively calculated in the rules section, resulting in a need to duplicate and nest many methods in order to simulate some conditions. This limitation could be reduced and flexibility could be added by creating a new method that would return the value of the most recently computed reservoir release. That release could then be evaluated in subsequent combo methods to arrive at the final release. *Priority: Moderate*

4. Reservoir releases are often made to satisfy consumptive use demands or other demands at a downstream location. A new method could be developed to simulate this operation, or the lookup capability mentioned in item 2, above, could be formulated to include a time series value as a variable in the lookup method. *Priority: Low*

5. Diversions are often taken from a point on a river where no dam exists. It would be helpful to be able to simulate such a diversion at a node within a RES-J operation. This could be done by adding a withdrawal method to a node component. *Priority: High*

6. It would be useful in modeling streamflow regulation to be able to identify the type of reservoir operation that produced a given flow in a river. For instance, a reservoir may make a release for a fish flow and a downstream municipal demand according to complex rules. Later operations or segments might require the ability to distinguish between these flows to determine how much may be diverted. RES-J could be modified to allow the tracking and output of multiple release time series, e.g., power, spill, and fish flow to meet this need. *Priority: Low*

7. RFC's that are implementing multiple reservoirs using RES-J may want to model all of their intermediate LAG-K models within the RES-J operation. This would require the RES-J LAG-K method to be modified to include the same capability as the LAG-K operation. *Priority: Moderate*

RES-SNGL

RES-SNGL is very effective at simulating single, independently operated reservoirs with known operating rules. Several enhancements would improve its functionality.

1. RFC's reported that the ADJUST utility in RES-SNGL does not function properly. The problem with the ADJUST utility in RES-SNGL should be fixed. *Priority: Moderate*

2. To meet the same need as was mentioned in RES-J item 2, above, a new scheme could be added to RES-SNGL with the functionality found in LOOKUP3. *Priority: Low*

CHANLOSS

The CHANLOSS operation is very effective at simulating diversions when the diversions do not change significantly from year to year. Frequently, specific operations in a river result in a diversion that is different than that specified in the CHANLOSS operation, and it is known that they will continue for a given period of time. The addition of run-time modifications to the CHANLOSS operation would improve its short-term forecast performance when the current diversions are different from the average values. *Priority: Low*

CHANLOSS is also limited to fixed monthly losses or losses as a linear function of discharge. The operation could be expanded to include an option to allow the computed loss or gain be a non-linear function of discharge. *Priority: Moderate*

CHANLOSS computes the resulting streamflow after the loss or gain is accounted for. It might be useful to generate a time series representing the actual gain or loss in addition to the resulting streamflow. *Priority: Low*

FLDWAV

Needs for more flexibility in modeling locks and dams were identified by RFCs and noted in the issues summary document. Enhancements to the lock and dam features in the FLDWAV operation could provide the needed flexibility. *Priority: Moderate*

NWSRFS Modification

One current constraint to modeling regulation within NWSRFS is that in an ESP simulation, operations are simulated one month at a time. This means that when a reservoir model is making a release decision for the last day of a month, it does not have any information concerning flows which are expected to occur on the first of the next month. Methods like MAXSTAGE in RES-J and schemes like STPOOLQ in RES-SNGL can not properly function across months.

NWSRFS could be modified to simulate an entire trace in ESP. Structurally, this would require only minor changes to the system, however, some consideration would need to be given to whether this would impact any individual operations. For example, RES-SNGL uses a SUMINF utility that sums inflow over the simulation period. SUMINF was not originally intended to sum inflow over a 1-year trace in ESP. *Priority: Low*

Current operations often depart from standard operating rules, and it may be known that the departure will continue for a time. This is generally handled with mods in the operational system, but these mods are not available in ESP. Some way of representing known departure from standard operating rules in ESP is needed. One approach would be to implement mods in ESP. *Priority: Low*

Reservoir regulation is often based on conditions downstream of the current reservoir or on a current water supply forecast. In either case, the previous execution of the forecast system will may include information that could be used to simulate these operations. Capability could be incorporated into the system or into a given operation to be able to consider time series or processed data from a previous forecast or ESP run in selecting regulation options. *Priority: Low*

New Tools

A new operation could be written that would allow equations to be written with time series treated as equation variables. Modeling streamflow regulation often requires the use of multiple arithmetic operations to compute a needed time series. This often results in complicated operations tables which are difficult to develop, understand, and support. An equation processor operation would provide flexibility that is not available in the existing operations and it would result in simpler operations tables. *Priority: Moderate*

A groundwater model could be developed as a new operation. This would provide a more straightforward way of modeling ground water-surface water exchanges. Currently, there is no simple way to model the impact of ground water pumping on surface water flows. *Priority: Low*

External Models

It may be satisfactory to use models which are external to the forecast system without incorporating their functionality into the forecast system. In some cases, these models may be executed at the RFCs. In other cases, these models may be executed by other agencies and results provided to RFCs for use in the forecast system. Some consideration would have to be given to whether RFCs could be dependent on results provided by another agency and whether a satisfactory backup plan could be developed.

Candidate external models may include reservoir models, water allocation models, groundwater models, and dynamic routing models.